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RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

EFFECTS OF INDUCTION-SYSTEM ICING ON AIRCRAFT-ENGINE

OPERATING CHARACTERISTICS

By Howard C. Stevens, Jr.

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Cleveland, Ohio

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SUMMARY

An investigation was conducted on a multicylinder aircraft engine on a dynamometer stand to determine the effect of induction-system icing on engine operating characteristics and to compare the results with those of a previous laboratory investigation in which only the carburetor and engine-stage supercharger assembly from the engine were used. The experiments were conducted at simulated glide power, low cruise power, and normal rated power through a range of humidity ratios and air temperatures at approximately sea-level pressure.

Induction-system icing was found to occur within approximately the same limits as those established by the previous laboratory investigation after making suitable allowances for the difference in fuel volatility and throttle angles. Rough operation of the engine was experienced when ice caused a marked reduction in the air flow. Photographs of typical ice formations from this investigation indicate close similarity to icing previously observed in the laboratory.

INTRODUCTION

At the request of the Air Materiel Command, Army Air Forces, an investigation has been conducted at the NACA Cleveland laboratory of the icing and de-icing characteristics of an engine induction system. Previous investigations included laboratory experiments to determine the icing characteristics (reference 1) and the effects of an automatic manifold-pressure regulator (reference 2).

The purpose of the experiments reported herein was to establish correlation between the results obtained in the previous laboratory

investigation using a carburetor-supercharger assembly operating with volatile nonleaded fuel (reference 1) with those obtained using an engine operating with service fuel of lower volatility. Icing characteristics of the engine were obtained during operation at simulated glide power, low cruise power, and normal rated power over a range of humidity ratios and dry-bulb air temperatures at approximately sea-level carburetor-deck pressure. The effects of icing on reducing the air flow and the cylinder-head temperature, altering the fuel-air ratio, and producing rough engine operation were obtained for low cruise and normal-rated power conditions. Photographic data of typical ice formations in the induction system were obtained to establish correlation with the previous laboratory results. The influence of an automatic pressure regulator on the performance of the engine during icing conditions at low cruise power was needed to determine the limits of serious icing for engine installations incorporating that type of control.

APPARATUS

The experiments were made with a multicylinder engine mounted on a dynamometer stand. Conditioned air was supplied through ducts to the carburetor at the desired dry-bulb temperature, humidity, and pressure; simulated rain was sprayed into the vertical portion of the duct above the carburetor entrance, as shown in figure 1. The dry refrigerated air was humidified by steam sprayed into the duct upstream of a filter to insure equalization. The amount of steam required for humidification was regulated by wet-bulb and dry-bulb air temperature indications from a special thermocouple psychrometer located upstream of the simulated-rain sprays similar to the installation described in reference 3.

The engine had a supercharger impeller-to-engine speed ratio of 9.6:1 as compared with the speed ratio of 8.1:1 of the carburetor and engine-stage supercharger assembly, which was used in the laboratory investigation (reference 1). The icing characteristics of the engine were thus expected to be slightly different from those of the carburetor-supercharger combination because of the different throttle angles for a given engine-speed and air-flow condition. In both cases, a pressure-type carburetor with a double throat was used; slight differences between carburetors were considered to be negligible for the purposes of this investigation. Both carburetors were fitted with special continuously variable fuel-metering plates to permit finer adjustment of mixture ratios.

A standard carburetor-entrance screen was used in these experiments; no protective screen was used in the experiments of reference 1. Addition of the screen was expected to introduce no measurable effect on icing

characteristics at temperatures above 32° F, but the screen was expected to accelerate the rate of impact-ice blocking below 32° F. The duct section immediately above the carburetor was so arranged that it could be readily disconnected and the carburetor removed for inspection and photographing of ice formations. A special supercharger inlet elbow, provided for the investigation reported in reference 4, fitted with special windows was used in these experiments to detect the presence of fuel-evaporation icing during engine operation.

A standard manifold-pressure regulator, which automatically operates the throttle to maintain constant manifold pressure, was installed on the carburetor for two runs.

The flow and temperature of the engine air, fuel, and simulated rain were indicated, together with carburetor-deck pressure, manifold pressure, metering suction differential, carburetor pressure drop, throttle angle, engine torque and speed, and cylinder-head temperature. Spark-plug-gasket thermocouples were installed for one run. The fuel used in these experiments was 28-R.

PROCEDURE

The conditions for all runs are listed in table I. The engine was operated at a carburetor-deck pressure of 29.3 inches of mercury absolute and selected air flows of 1540, 4620, and 7700 pounds per hour, corresponding approximately to glide power, low cruise power, and normal rated power, respectively.

The mixture control was used to set the fuel flow within the arbitrary limits shown in figure 2, which is approximately correct for the carburetor. The carburetor-deck pressure was controlled within ± 0.1 inch of mercury absolute to simulate level flight at constant airspeed and the engine speed was maintained constant by manually adjusting the field rheostat of the dynamometer. Once set, the throttle and mixture-control settings were not altered during a run except when the manifold-pressure regulator was used.

The simulated-rain injection was varied from 25 to 1000 grams per minute, corresponding to conditions of moderate rain (less than $1/2$ gram/cu meter) and excessive rain (more than 2 grams/cu meter). The rain temperature was varied between 47° and 79° F. The fuel temperature was maintained at about 60° F.

When the engine was operating under approximately the desired conditions, steam and water sprays were turned on and adjustments

made to obtain the selected conditions of humidity ratio and relative humidity of the engine air. Steam and water sprays were then diverted to bypass lines, thus removing any ice that had formed and at the same time maintaining the correct settings for humidification and simulated rain. The air flow was then readjusted to a rate lower than the desired rate to compensate for the increase in flow caused by the injection of steam and water. Injection was again started and air flow, fuel flow, engine speed and torque, carburetor pressure drop, manifold pressure, metering suction differential, carburetor-deck pressure, and air temperature were recorded at regular intervals. During one run spark-plug-gasket temperatures were taken.

For two runs, when the manifold-pressure regulator was in operation, the procedures were similar except that throttle angle was automatically adjusted by the regulator during icing.

At the end of each run, ice formations were observed through windows in the supercharger inlet elbow or were studied and photographed by stopping the engine and quickly removing the carburetor.

RESULTS AND DISCUSSION

Results of the investigation fall into two categories: effects that could be correlated with the results of the laboratory investigation and effects that pertained to engine operation and could not be obtained using the carburetor and engine-stage supercharger assembly.

Correlation with Previous Laboratory Investigation

For correlation with the laboratory investigation, the results from table I for simulated low cruise and normal rated power are presented in figures 3 and 4, respectively, with the icing characteristics from reference 1.

In this report, as in reference 1, icing that in 15 minutes caused a 2-percent or greater drop in air flow was designated serious. The difficulty in observing and obtaining rapid access to the supercharger inlet elbow prevented the detection of most nonserious icing, which is reported as visible icing in reference 1. The results of all runs are given in table I with verbal description of the type of icing.

Of the five runs (1 to 5) made at simulated glide power, four were made with dry-bulb air temperatures from 41.5° to 52° F and relative humidities from 68 to 100 percent and did not result in serious icing.

The other run, with a dry-bulb air temperature of 40° F and saturated air plus simulated-rain injection of 50 grams per minute, did result in serious icing. Inspection at the end of each of these runs disclosed an oil film on the under side of the throttles and on the walls of the inlet elbow caused by leakage of oil past the supercharger seals at the low manifold pressure, which would have reduced the tendency of ice to adhere to these surfaces. Presumably, icing would have been serious with such atmospheric conditions and low throttle openings had the oil film not been present.

Serious-icing conditions for the complete engine at low cruise power (fig. 3) fell below the limit established in the laboratory investigation as might be expected because the 28-R fuel is less volatile and hence will produce less evaporative cooling than AN-F-22 fuel.

For the normal-rated-power conditions (fig. 4), however, serious-icing points more nearly correspond to the limit established in the laboratory despite the less volatile fuel in the engine runs.

Icing seriously affects engine air flow at reduced throttle angles because both the increased carburetor pressure drop and greater turbulence in the fuel spray below the throttles produce a greater temperature depression and the resultant increased icing quickly obstructs the smaller throttle opening.

Photographs of typical ice formations from this investigation, shown in figures 5, 6, and 7, for runs 28, 29, and 30, respectively, at low cruise power indicate close similarity to icing previously observed in the laboratory. Throttling and fuel-evaporation ice formed on the carburetor throttles and inlet elbow at a dry-bulb air temperature of 45° F with saturated air (fig. 5). Heavier formations resulting from a dry-bulb air temperature of 40° F, saturated air, and simulated-rain injection of 100 grams per minute are shown in figure 6. Figure 7 shows ice formations after a run at a dry-bulb air temperature of 20° F with saturated air plus simulated-rain injection of 50 grams per minute. Careful inspection of figure 7(a) reveals impact ice remaining on the carburetor entrance screen, whereas in figures 7(b) and 7(c), ice on the throttles and in the inlet elbow is evident. Ice formations at the edge of the throttles that seriously restricted air flow may be observed in figures 5 to 7.

Effect on Engine Operating Characteristics

Charge-air flow. - The primary effect of induction-system icing in the engine was throttling of the charge-air flow with corresponding reductions in manifold pressure and engine horsepower. Typical results of serious icing (run 14) are shown in figure 8. At the end of 10 minutes, the air flow had dropped to 63 percent, the manifold pressure to 79 percent, and the horsepower to 62 percent of their initial values.

In flight operation with manually controlled throttles and constant-speed propellers, the decrease in manifold pressure normally serves as a warning that induction-system icing is occurring. In 12 of the low-cruise-power runs at fixed throttle setting, charge-air flow dropped at least 2 percent. In runs 31 and 32 under similar conditions, but with the manifold-pressure regulator in operation, the throttle was automatically opened to maintain nearly constant air flow during icing conditions. Figure 9 shows that the throttles opened from 26° to 38° during icing while the manifold pressure was maintained nearly constant, thereby eliminating the normal warning of the occurrence of induction-system icing. If such a process were continued, the throttles would either reach the limit of opening or would be prematurely stopped by ice formations. Because no further opening could be effected, continued icing would cause a loss of manifold pressure that could not be recovered.

Fuel-air ratio. - In some cases impact icing on the air-metering parts of the carburetor adversely affected the fuel metering in the carburetor, or fuel-evaporation icing interfered with the injection of fuel into the supercharger inlet elbow by forming around the fuel spray nozzle (reference 1) and causing rough engine operation. This rough operation was detected by abnormal engine vibration or irregular engine noise. Four of the fifteen serious-icing runs at low cruise power and all of the serious-icing runs at normal rated power resulted in rough engine operation. Rough operation occurred only after icing had reduced the charge-air flow more than 2 percent.

In order to investigate the possibility that significant changes in fuel-air ratio were the cause of roughness or loss of power in addition to that due to the reduction in air flow, the ratio of the observed values of fuel-air ratio obtained during icing to the value from the lower limit curve of the normal carburetor-metering characteristics (fig. 2) was computed and plotted against time, as shown in figures 8 and 9. Large deviations from 1.00 in this ratio mean that the fuel-air ratio has changed from the value that would normally occur at the observed air flow. The ratio of the observed horsepower to the anticipated value for the observed air flow was determined and plotted in a similar manner.

For run 14 both the horsepower and fuel-air ratio remained nearly equal to the values normally anticipated for the reduced air flows (fig. 8(a)), indicating that the only measured effect was the throttling of the air flow. In two runs, 21 and 22 (footnote to table I), the metering suction differential was higher than anticipated because of impact ice on the air-metering parts of the carburetor and the resulting fuel-air ratios were also high, reaching 0.097 and 0.127, respectively. In contrast, run 31 (fig. 9) shows excessive decreases in both fuel-air ratio and horsepower. The metering suction differential pressure decreased below the normal value for the observed air flow but fuel flow was normal for the observed metering differential. In another run (33), the metering suction differential was lower than anticipated and the fuel-air ratio dropped to 0.056. Of the seven runs in which rough operation occurred, three (runs 22, 31, and 33) were characterized by abnormal fuel-air ratios.

Spark-plug-gasket temperature. - Spark-plug-gasket temperatures, measured only during run 14, are shown in figure 8(b). All temperatures after icing started were lower than the initial values with the exception of cylinder 2 in the right bank. The downward trend and the similarity of the curves is a logical effect of the injection of simulated rain and indicates no change in the normal mixture distribution. The injection of quantities of simulated rain greater than the rate of 50 grams per minute used in run 14 would produce a correspondingly greater depression of cylinder-head temperatures and cause rough operation.

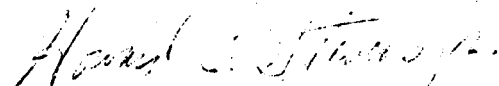
SUMMARY OF RESULTS

From a study of the effects of induction-system icing in a multicylinder engine mounted on a dynamometer stand, the following results were obtained:

1. Correlation existed between the icing characteristics of the complete engine and those of a laboratory setup (used in a previous investigation), consisting only of the carburetor and supercharger assembly, after suitable allowances were made for differences in fuel volatility and throttle angle in the two investigations.
2. Rough engine operation occurred only after icing had reduced the charge-air flow more than 2 percent.
3. In three of the seven runs in which rough operation occurred, abnormal fuel-air ratios were recorded.

4. An automatic manifold-pressure regulator prevented loss in charge-air flow or manifold pressure during two 15-minute runs at serious-icing conditions but did so without giving warning of the potentially serious ice formations existing on the throttles.

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TABLE I - CONDITIONS AND RESULTS OF ICING INVESTIGATION OF
MULTICYLINDER ENGINE INSTALLED ON DYNAMOMETER STANDNATIONAL ADVISORY
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temperature, approx. 60° F.]

Run	Simu- lated power	Initial charge- air flow (lb/hr)	Engine speed (rpm)	Initial fuel-air ratio	Dry-bulb air tem- perature (°F)	Simulated- rain injection (gram/min)	Total humidity ratio (lb water/ lb dry air)	Type of icing	Remarks
1	Glide	1580	2200	0.079	50.5	0	0.00530	Nonserious	
2		1565	2000	.080	52	0	.00825	Nonserious	
3		1585	2200	.078	41.5	0	.00470	Nonserious	
4		1600	2200	.078	42	0	.00564	Nonserious	
5		1550	2200	.077	40	50	.00908	Serious	
6	Low cruise	4655	2000	0.080	46	25	0.00739	Serious	
7		4660	2000	.082	47	50	.00849	Serious	
8		4665	2000	.083	45	100	.00939	Serious	
9		4635	2000	.079	47	175	.01180	Serious	
10		4695	2000	.082	48	175	.01200	Nonserious	
11		4675	2000	.087	46	250	.01362	Nonserious	
12		4640	2000	.079	46	0	.00655	Nonserious	
13		4675	2000	.080	46	1000	.03490	Nonserious	
14		4575	2000	.077	47	50	.00829	Serious	(a)
15		4625	2000	.078	35.5	50	.00581	Nonserious	
16		4655	2000	.079	33	0	.00252	None	
17		4605	2000	.077	51	0	.00453	Nonserious	
18		4550	2000	.076	56	0	.00655	Nonserious	
19		4655	2000	.080	55	0	.00895	None	
20		4655	2000	.079	54.5	50	.01051	Nonserious	
21		4635	2000	.077	20.5	50	.00356	Nonserious	(b)
22		4655	2000	.080	25	250	.00980	Serious	(c), (d)
23		4695	2000	.077	26	100	.00565	Serious	(d)
24		4685	2000	.081	34	0	.00375	Serious	
25		4640	2000	.078	44	0	.00565	Serious	
26		4640	2000	.079	51	0	.00668	Serious	
27		4620	2000	.078	53	0	.00673	Nonserious	
28		4600	2000		45.5	0	.00643	Serious	
29		4680	2000	.081	40	100	.00802	Serious	
30		4810	2000	.083	20	50	.00352	Serious	
31		4625	2000	.078	40	250	.01238	Serious	(d), (e), (f)
32		4790	2000	.080	40.5	100	.00796	Serious	(d), (f)
33	Normal rated	7760	2400	0.094	40	250	0.00949	Serious	(d), (g)
34		7735	2600	.092	34.5	0	.00418	Nonserious	
35		7695	2600	.093	35.5	50	.00512	Serious	(d)
36		7710	2600	.093	35	250	.00861	Serious	(d)
37		7410	2600	.093	48	50	.00796	Nonserious	
38		7440	2600	.093	46	250	.01099	Nonserious	

- (a) Spark-plug-gasket temperatures were measured.
 (b) Metering suction differential increased above value anticipated for observed air flow, causing fuel-air ratio to increase to 0.097.
 (c) Metering suction differential increased above value anticipated for observed air flow, causing fuel-air ratio to increase to 0.127.
 (d) Rough engine operation occurred.
 (e) Metering suction differential decreased below value anticipated for observed air flow, causing fuel-air ratio to decrease to 0.059.
 (f) Manifold-pressure regulator operated throttles.
 (g) Metering suction differential decreased below value anticipated for observed air flow, causing fuel-air ratio to decrease to 0.056.

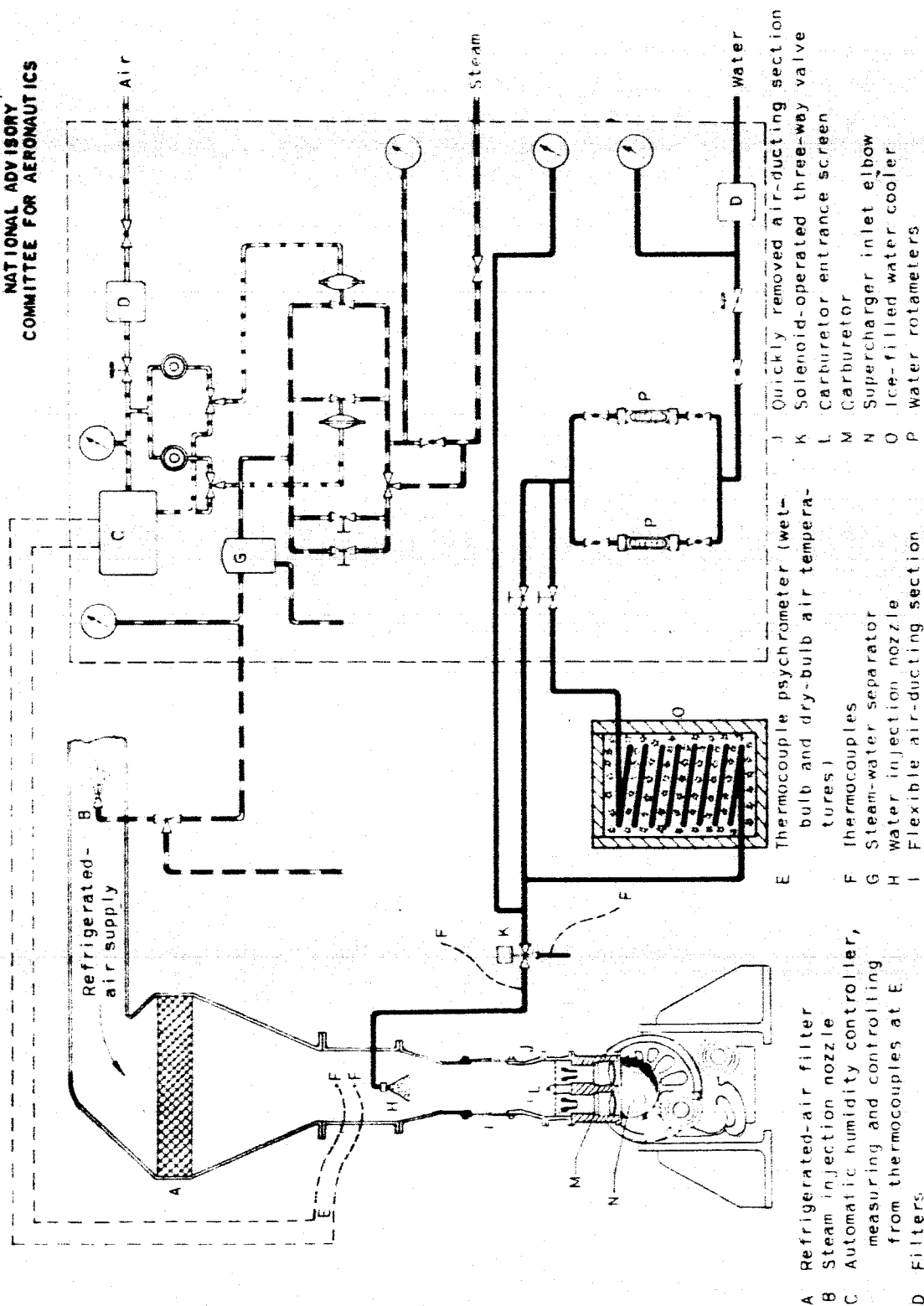


Figure 1. - Schematic diagram of humidifying and temperature-control apparatus for induction-system, investigating investigation of multicylinder engine.

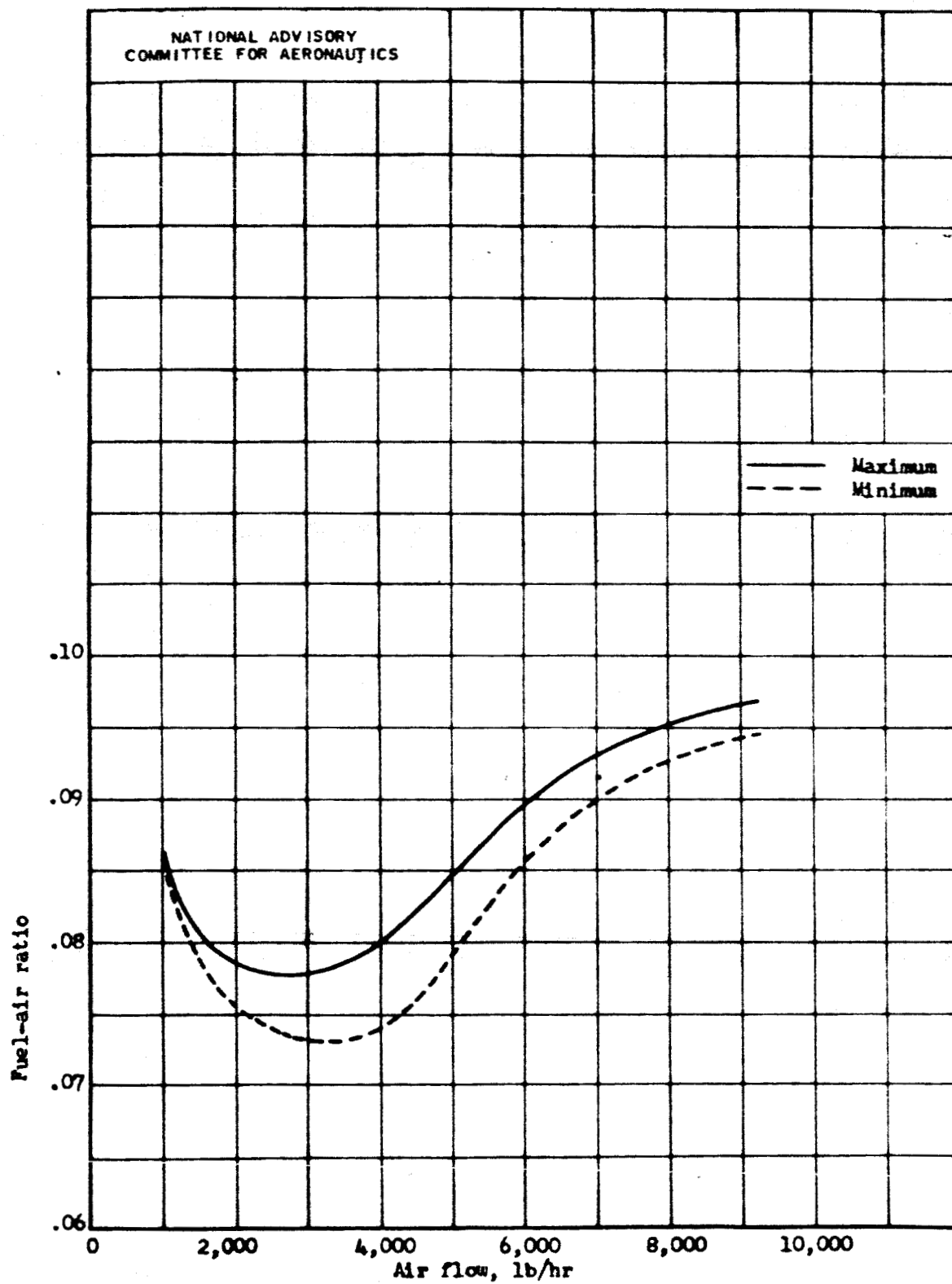


Figure 2. - Approximate carburetor metering characteristics.

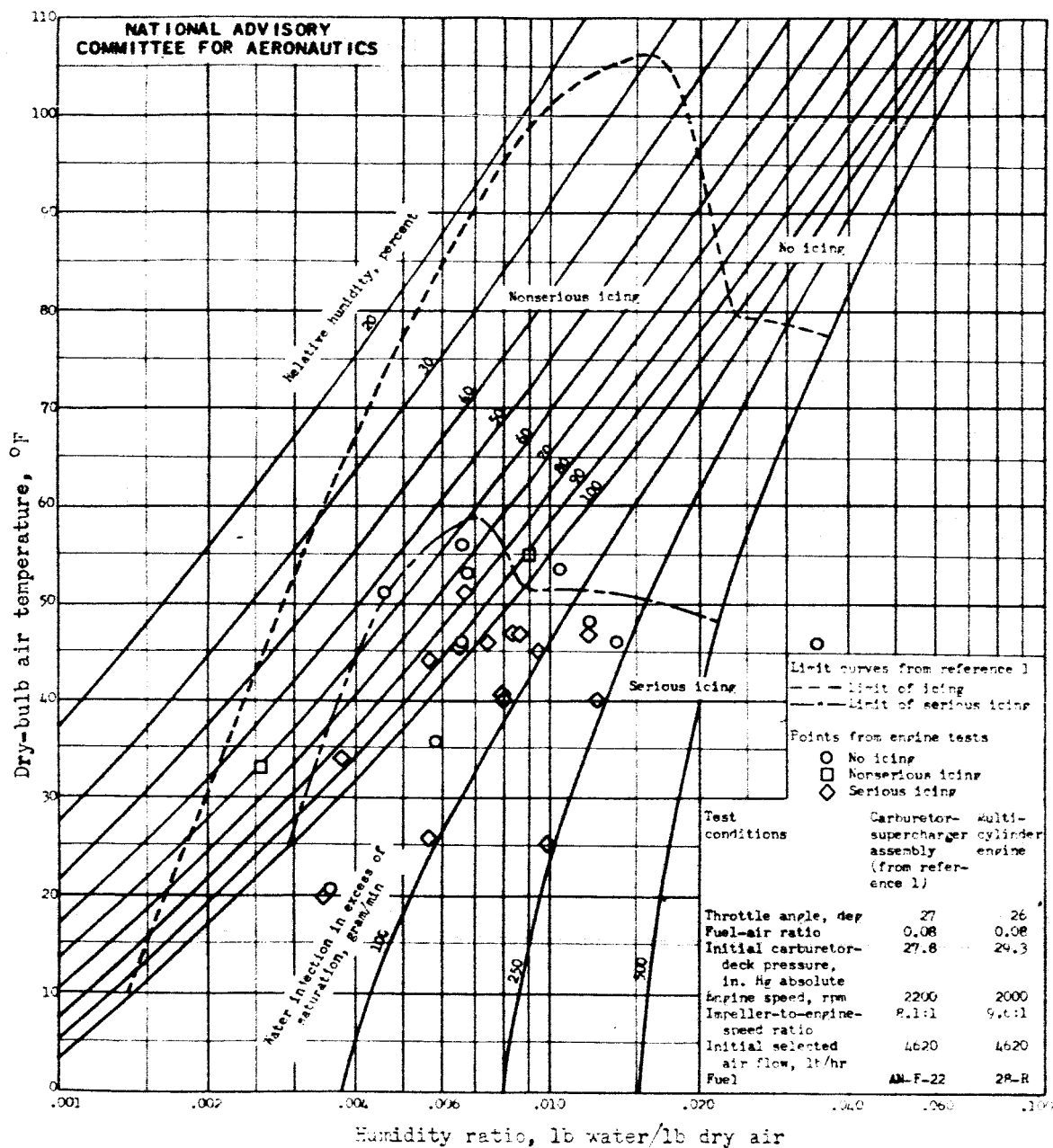


Figure 3. - Comparison of induction-system icing characteristics of multicylinder engine and carburetor-supercharger assembly at simulated low cruise power.

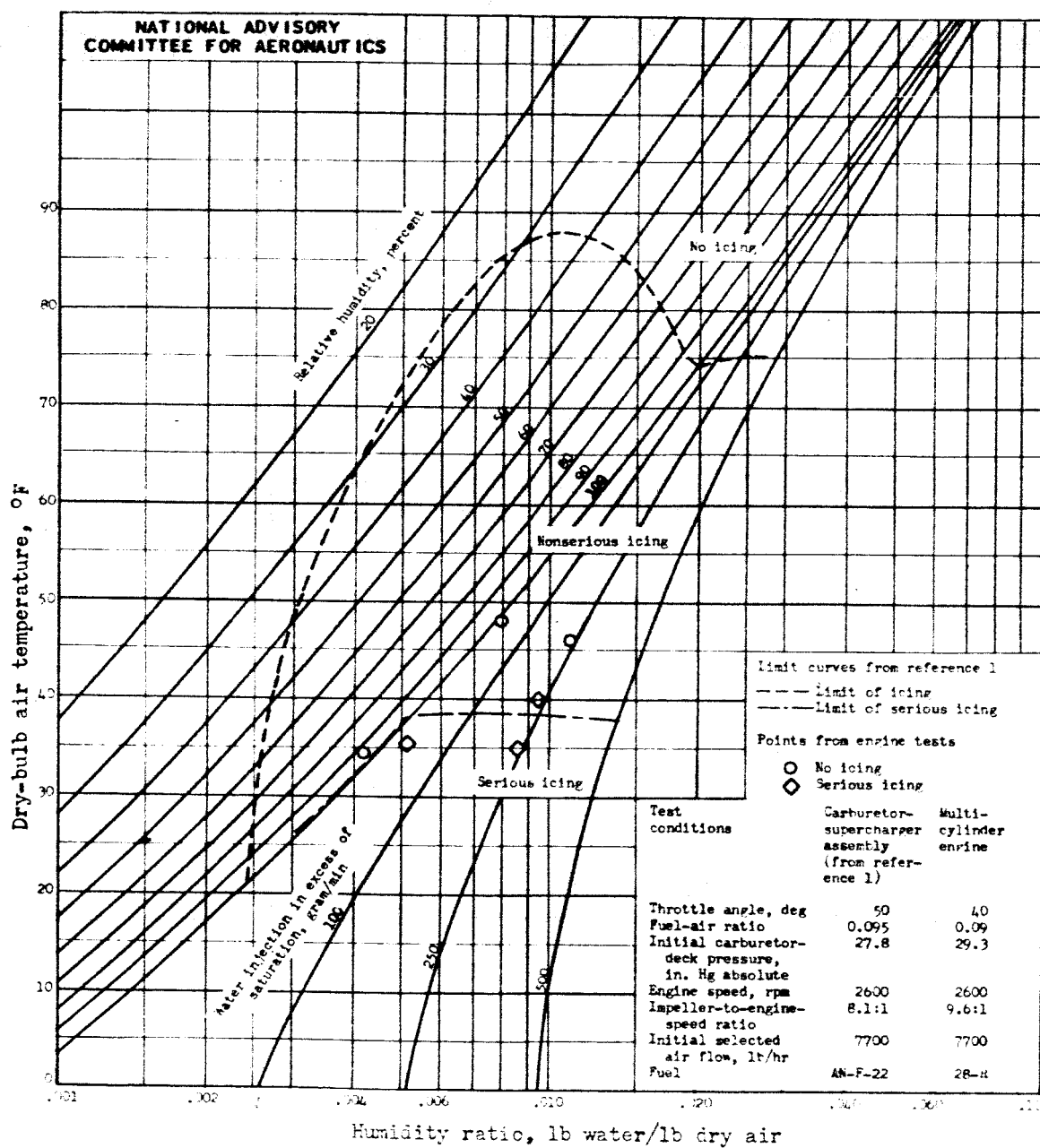
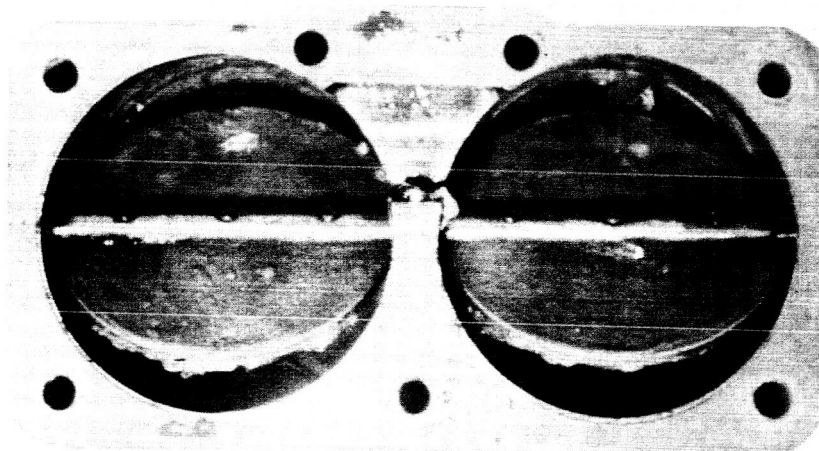
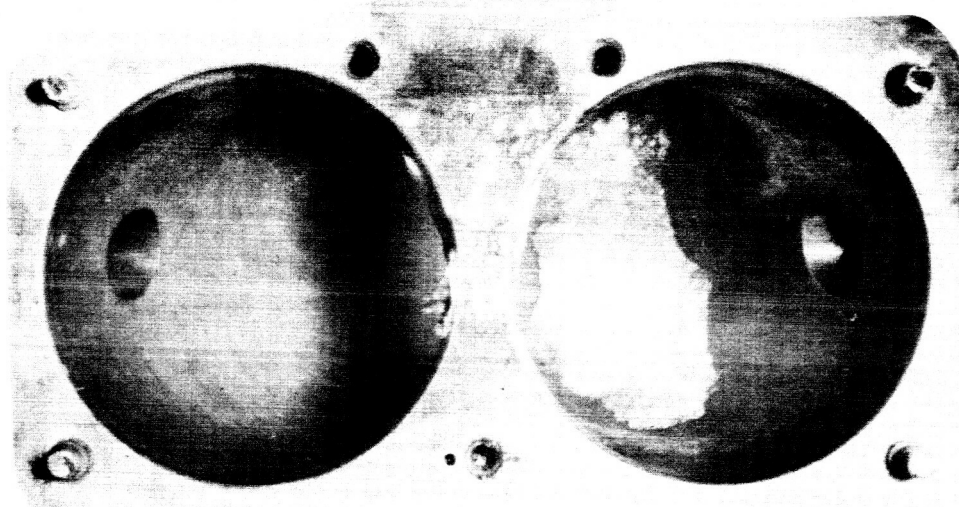


Figure 4. - Comparison of induction-system icing characteristics of multicylinder engine and carburetor-supercharger assembly at simulated normal rated power.



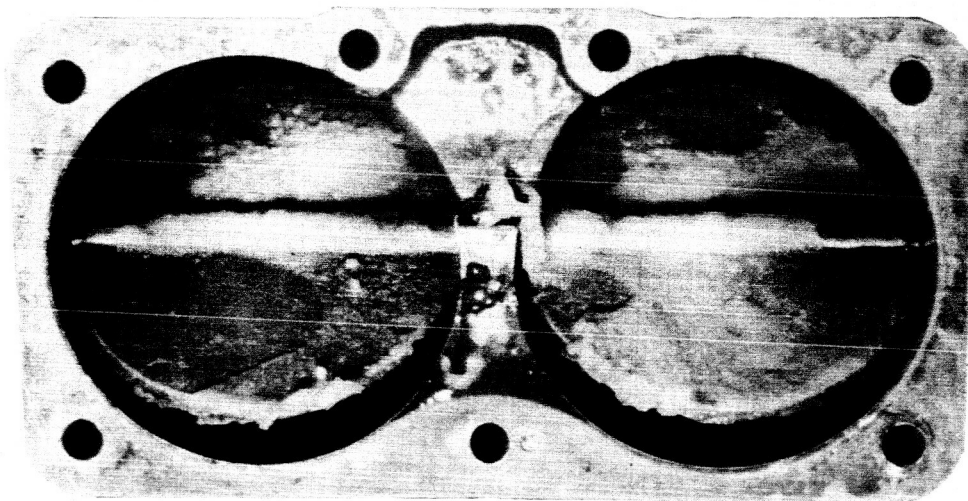
(a) Bottom view of carburetor showing throttling-ice and fuel-evaporation-ice formations.



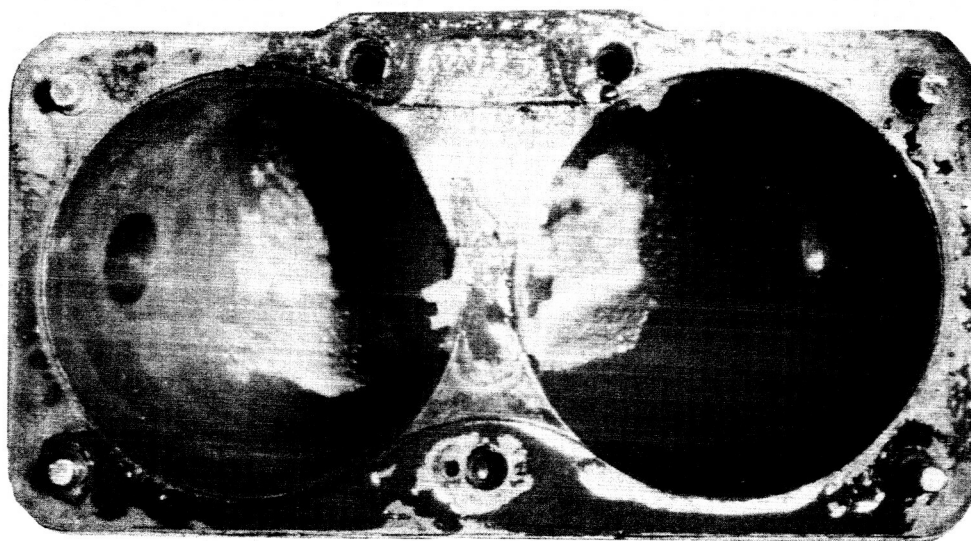
(b) View into supercharger inlet elbow showing fuel-evaporation-ice formations.

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Figure 5. - Serious icing after 12 minutes of engine operation. Simulated power; low cruise; initial air flow, 4600 pounds per hour; dry-bulb air temperature, 45.5° F; simulated-rain injection, 0 grams per minute; saturated air; throttle angle, 26° . Run 28.



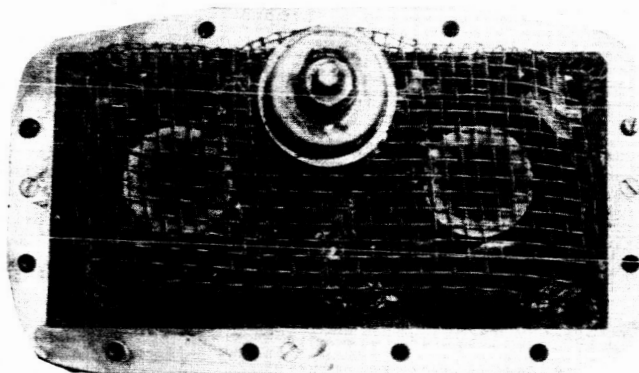
(a) Bottom view of carburetor showing throttling-ice and fuel-evaporation-ice formations.



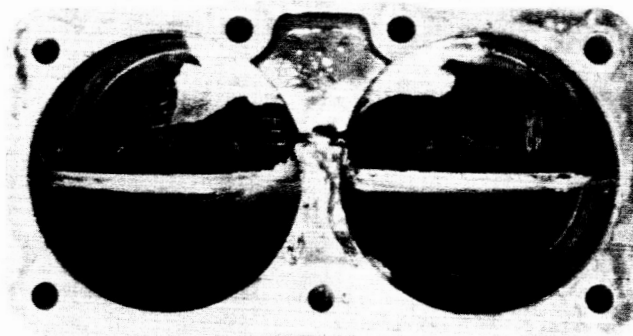
(b) View into supercharger inlet elbow showing fuel-evaporation-ice formations.

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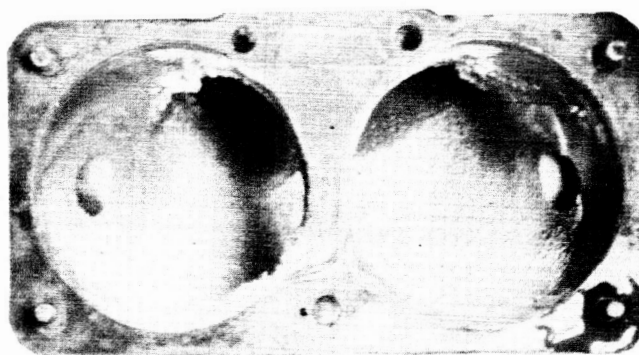
Figure 6. - Serious icing after 6 minutes of engine operation. Simulated power, low cruise; initial air flow, 4680 pounds per hour; dry-bulb air temperature, 40° F; simulated-rain injection, 100 grams per minute; saturated air; throttle angle, 26° . Run 29.



(a) Top view of carburetor with entrance screen showing impact-ice formations.



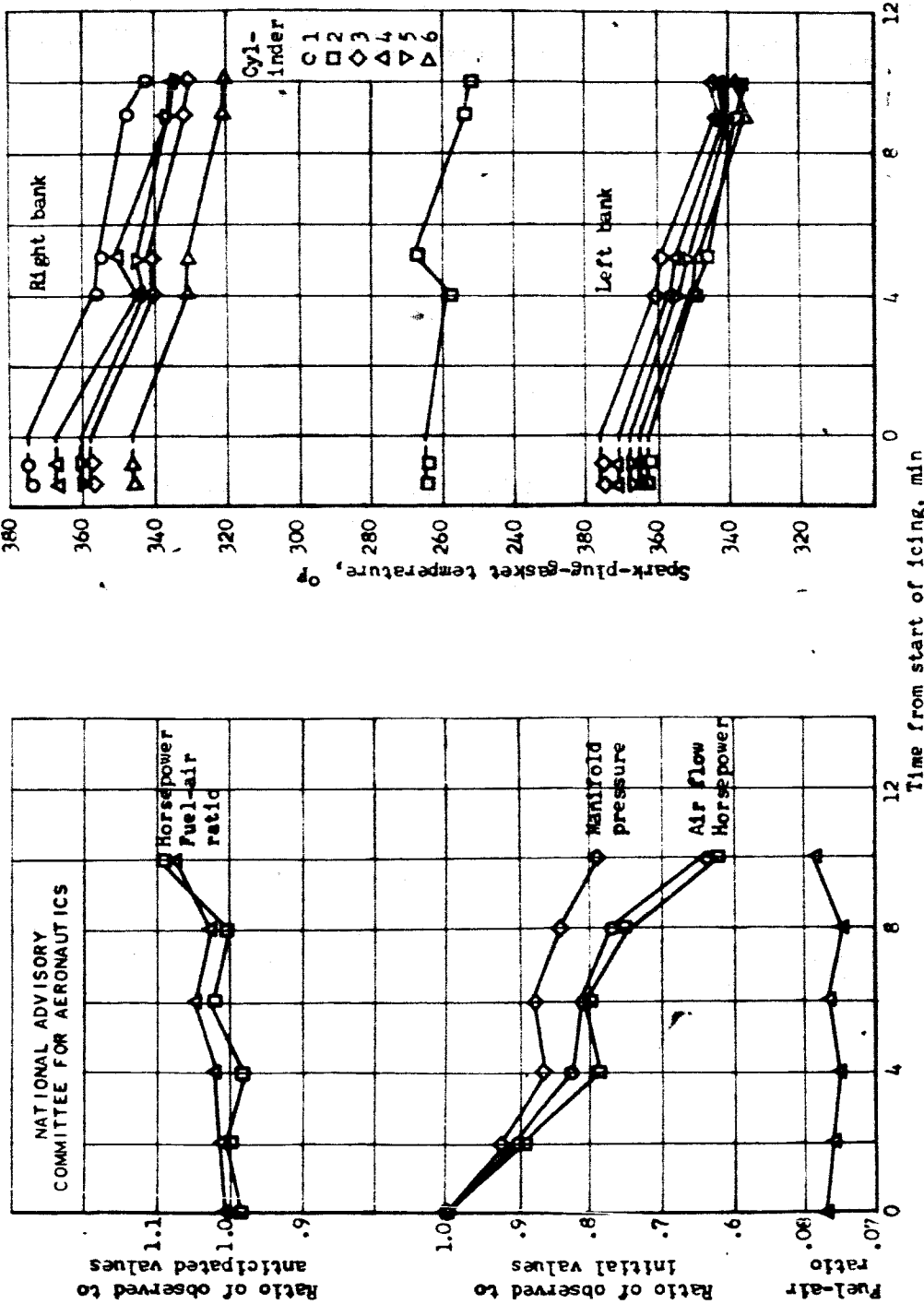
(b) Bottom view of carburetor showing throttling-ice, fuel-evaporation-ice, and impact-ice formations.



(c) View into supercharger inlet elbow showing fuel-evaporation-ice and impact-ice formations.

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Figure 7. - Serious icing after 2 minutes of engine operation. Simulated power, low cruise; initial air flow, 4810 pounds per hour; dry-bulb air temperature, 20° F; simulated-rain injection, 50 grams per minute; saturated air; throttle angle, 26°. Run 30.



(a) Effects of icing on carburetor and engine performance. (b) Effects of icing on engine temperatures.

Figure 8. - Results of serious icing. Simulated power, low cruise; initial air flow, 4575 pounds per hour; engine speed, 2000 rpm; dry-bulb air temperature, 47° F; simulated-rain injection, 50 grams per minute. Run 14.

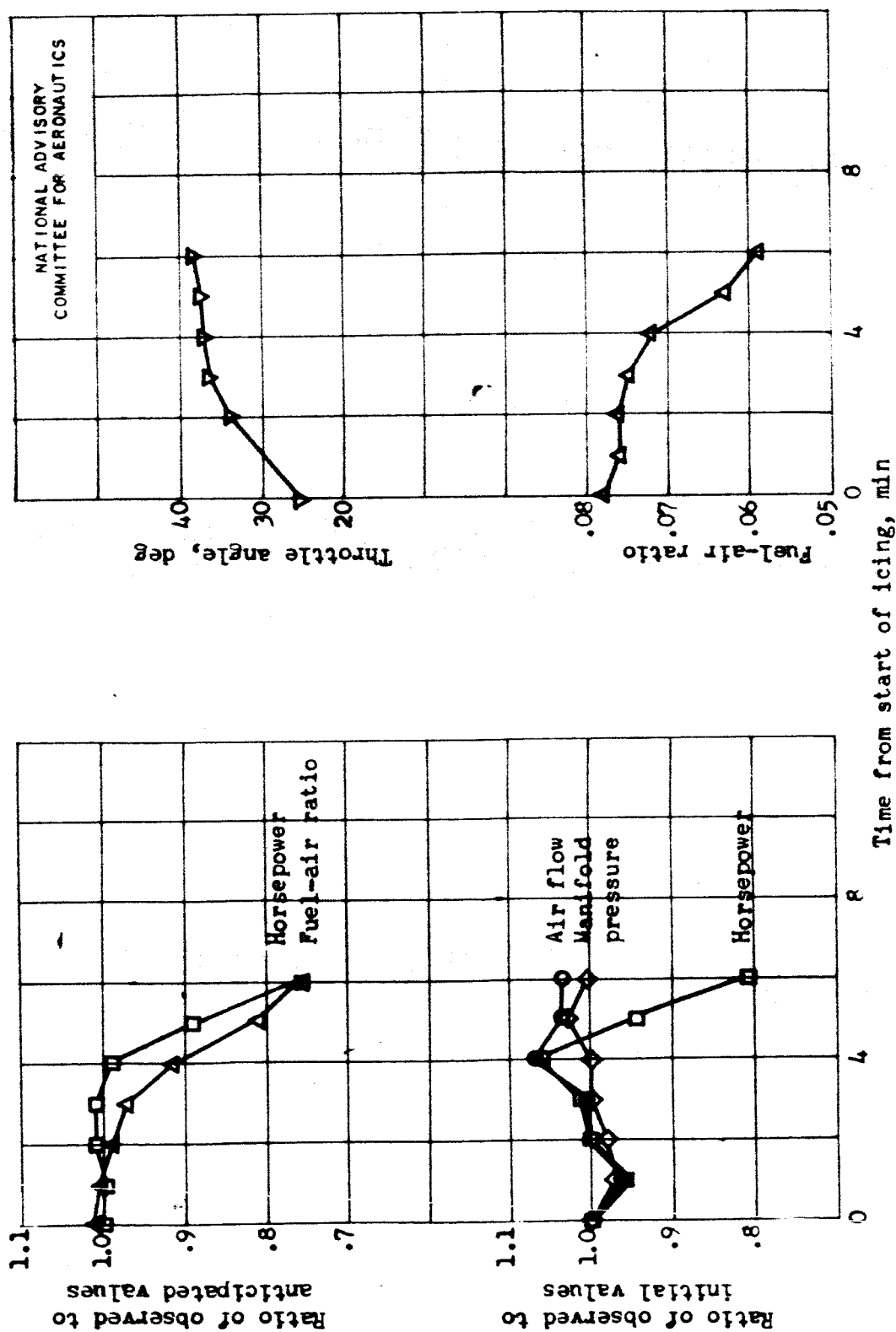


Figure 9. - Results of serious icing with manifold-pressure regulator. Simulated power, low cruise; initial air flow, 4625 pounds per hour; engine speed, 2000 rpm; dry-bulb air temperature, 40° F; simulated-rain injection, 250 grams per minute. Run 31.